Fifth Symposium on Lidar Atmospheric Applications (at 91st AMS Annual Meeting)
Seattle (Wa), 23–27 January 2011

A case for *more* multiple scattering lidar from space: Analysis of four LITE pulses returned from a marine stratocumulus deck

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… with ideas, papers, discussions, critique, and help from/by many colleagues:

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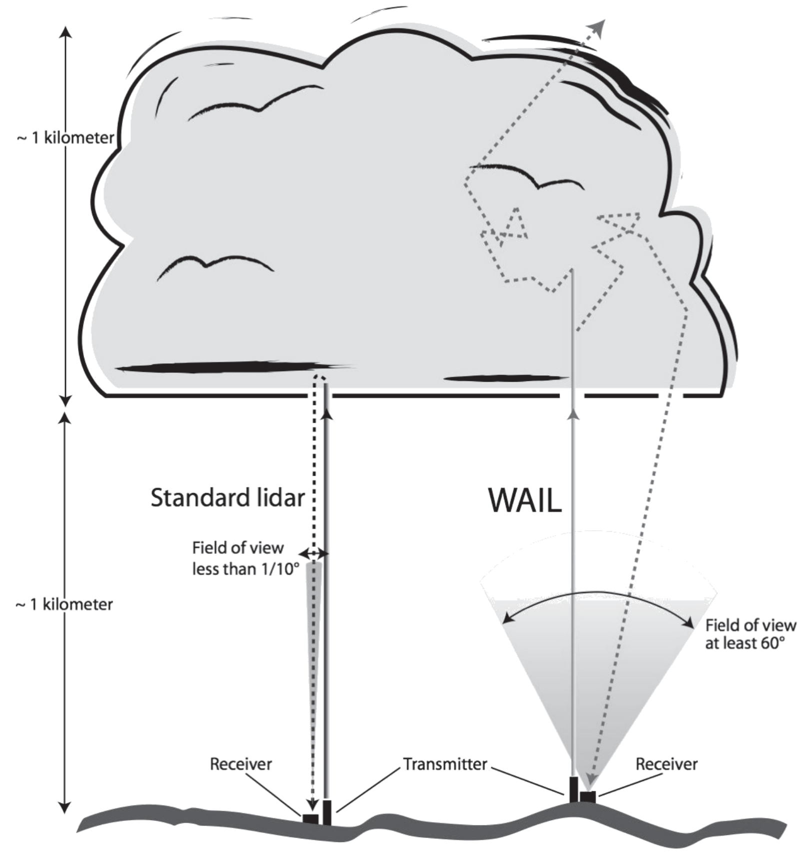
Bob Cahalan (NASA - GSFC)
Tamas Várnai (NASA - GSFC)
Matt McGill (NASA - GSFC)
Jim Spinhirne (NASA - GSFC)
Mark Vaughan (NASA - LaRC)
Graeme Stephens (JPL, ex-CSU)
Igor Polonsky (CSU)
Frank Evans (U of Colorado)
Ed Eloranta (U of Wisconsin)
Steve Love (LANL)
Luc Bissonnette (DREV, ret.)
Robin Hogan (U of Reading)
Nicola Pounder (U of Reading)



Outline:

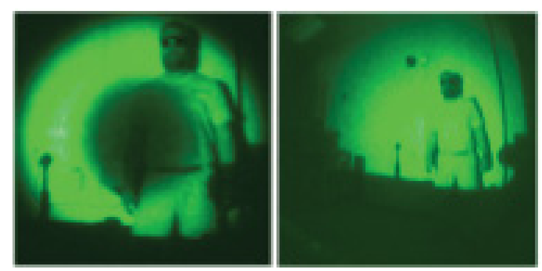
Signal Physics for Multiple-Scattering Cloud Lidar

SNR Estimation

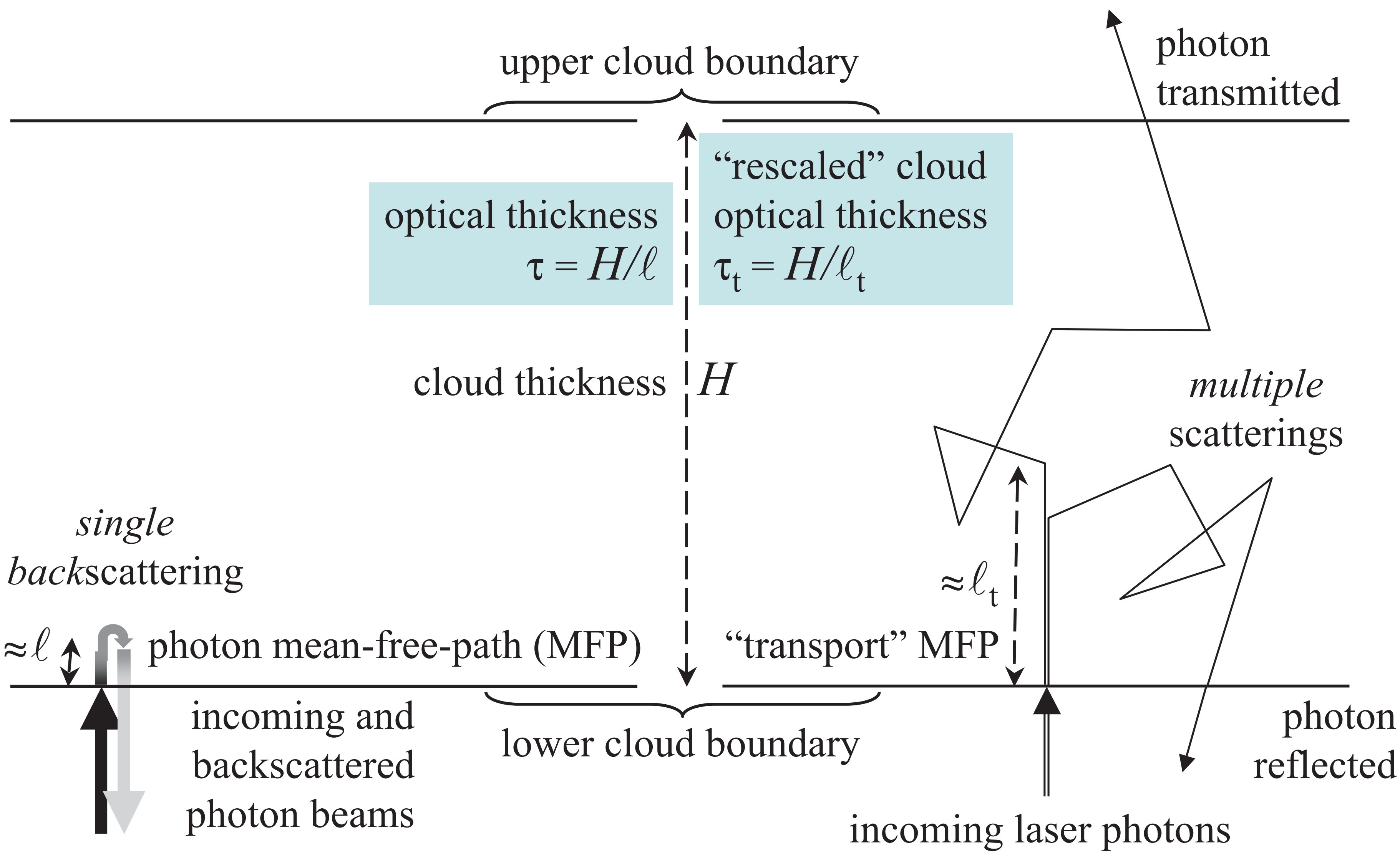
Cloud Property Retrievals

- **several techniques**
- **application to LITE data**
- **relation to O2 A-band**

Summary



Dense clouds: Standard backscatter lidar versus multiple-scattering cloud lidar



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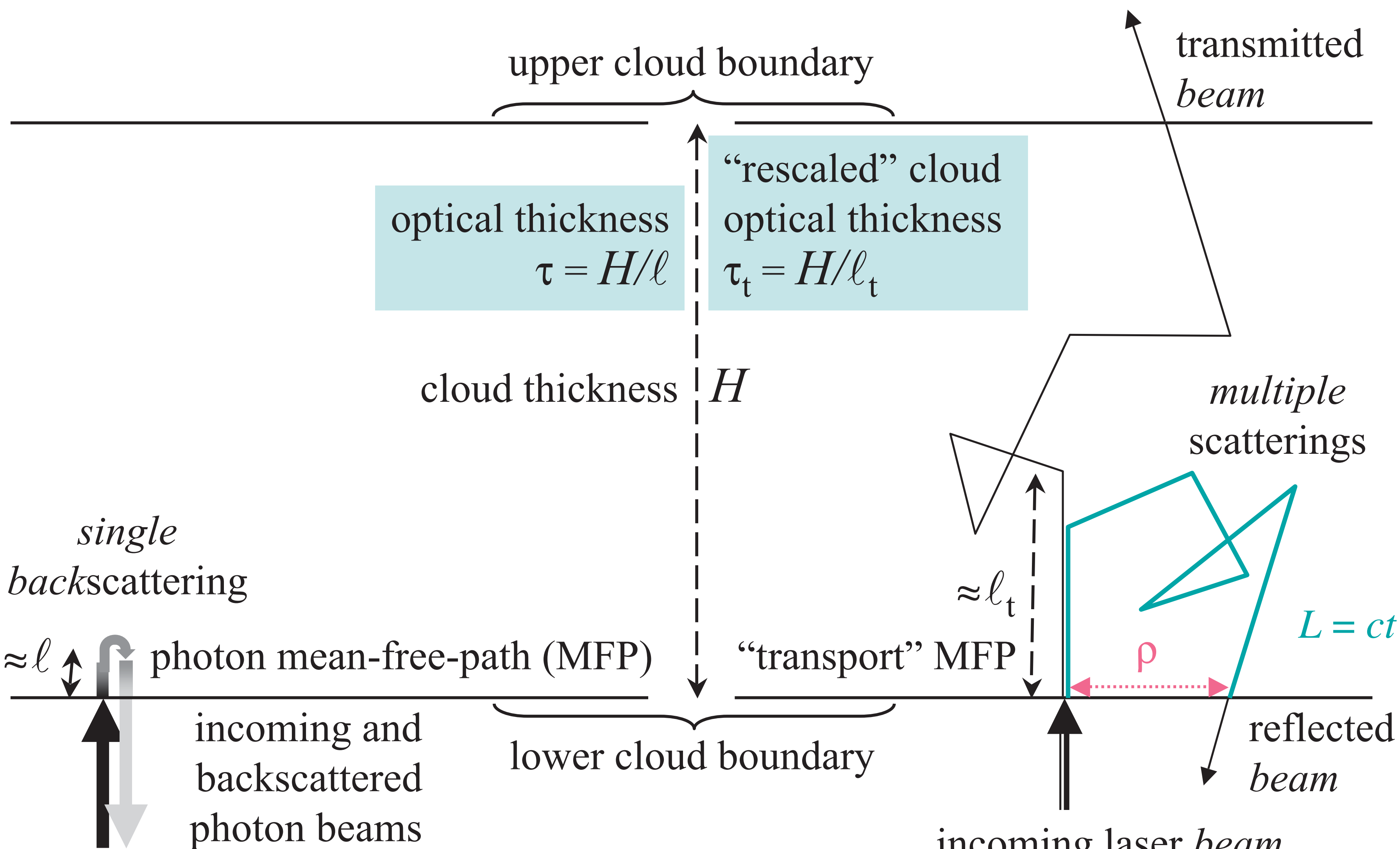

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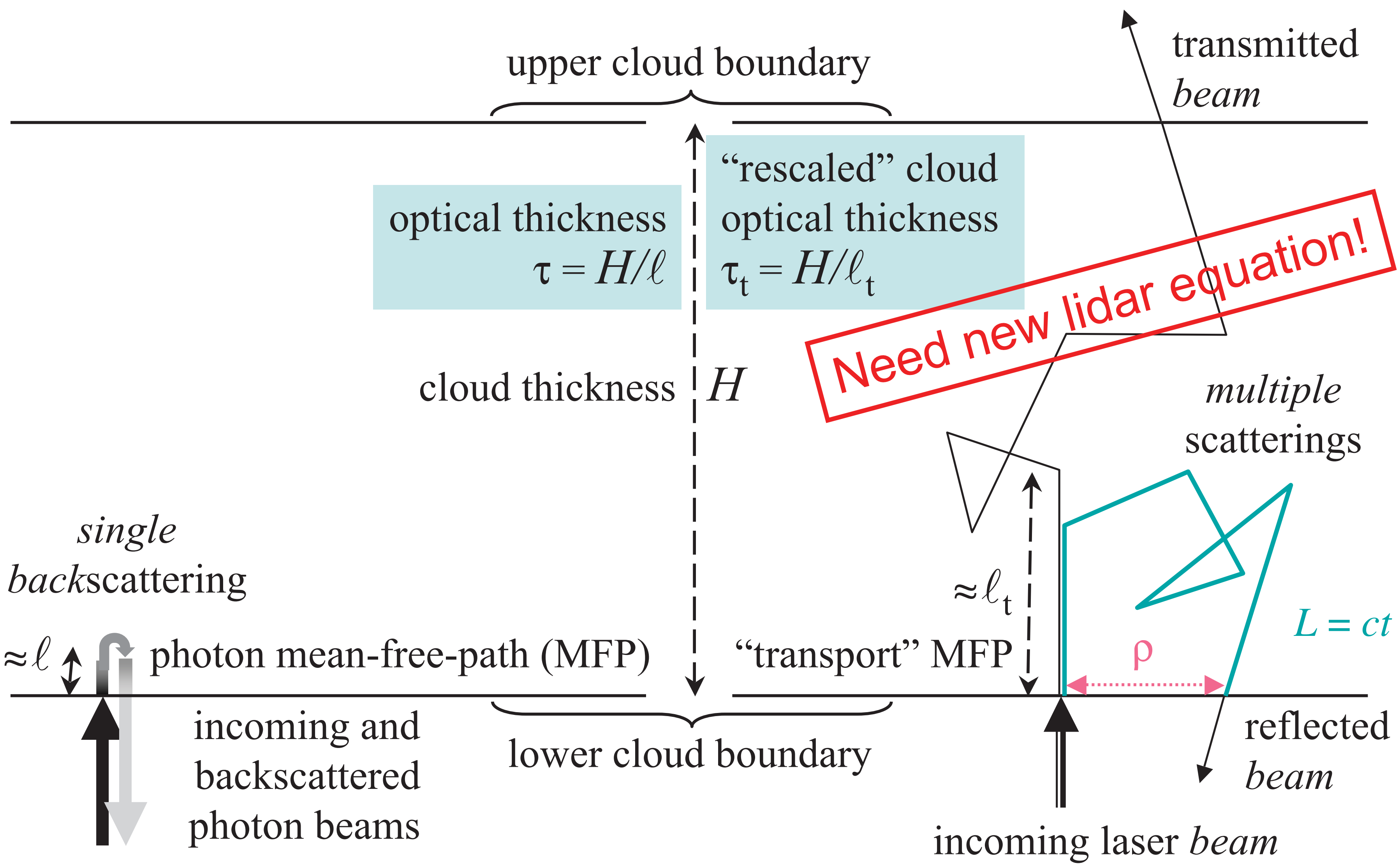
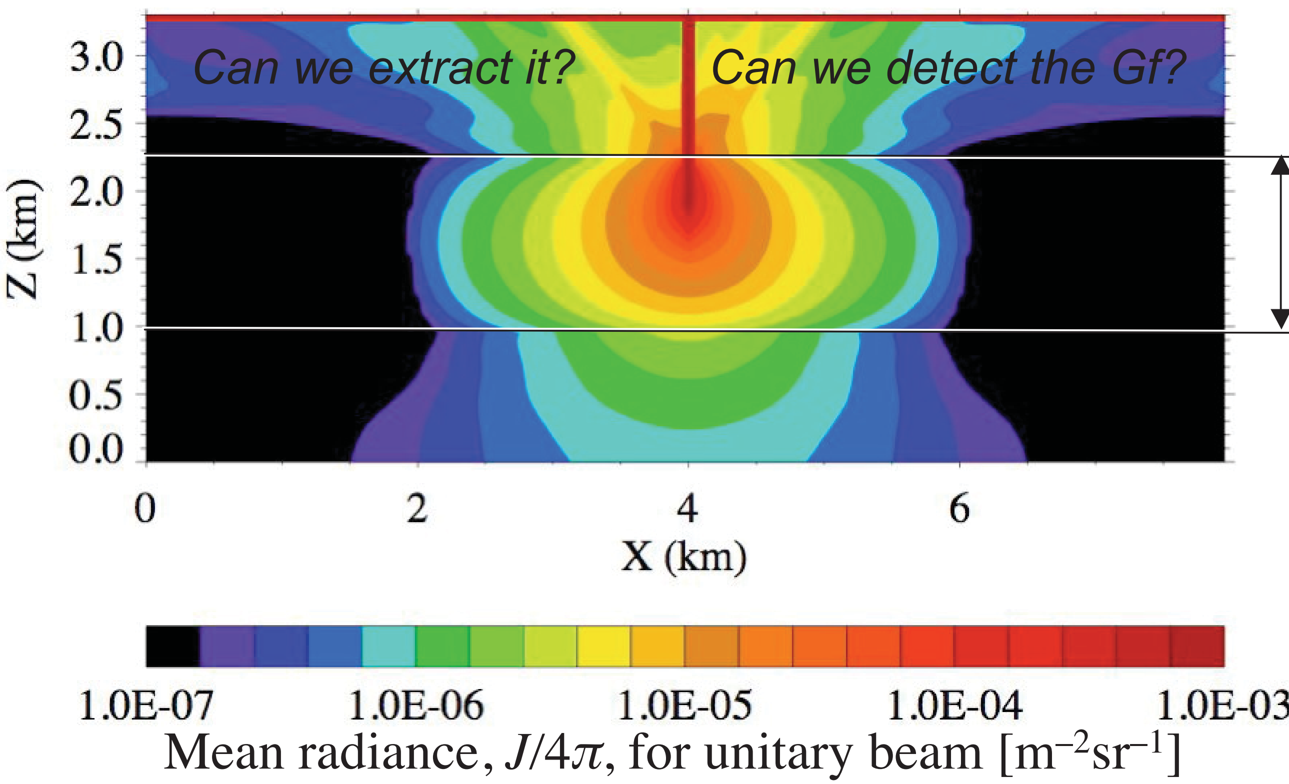


Dense clouds: Standard backscatter lidar versus multiple-scattering cloud lidar

With no absorption at common laser wavelengths (e.g., 532 nm), the diffuse radiance field (Green function) permeates the whole cloudy medium.
➔ It therefore contains information about the whole cloud.



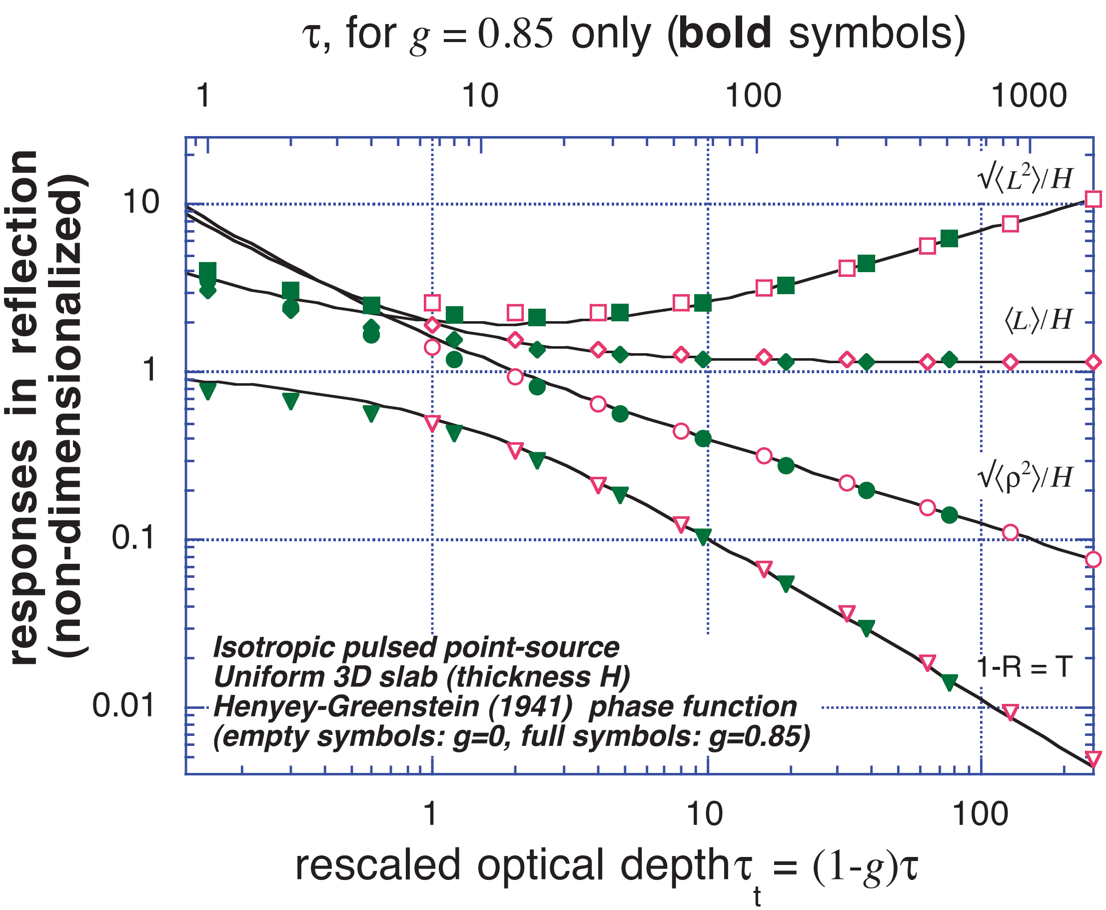
C1 phase function
$g \approx 0.85$

$H = 1.2$ km
$\tau = 36$

$(1-g)\tau \approx 5.4$
$\ell_t \approx 0.22$ km

SHDOM simulation of narrow beam (search light) problem, courtesy of Frank Evans (U. of Colorado)

Exact diffusion theory, for moments



Solid lines:
diffusion expressions
(closed-form)

Symbols:
Monte Carlo
3D RTE solution

Asymptotic slopes: derived "on a back of an envelop" (see extra slides)

Davis, A.B., R.F. Cahalan, J.D. Spinhirne, M.J. McGill, and S.P. Love, 1999: Off-beam lidar: An emerging technique in cloud remote sensing based on radiative Green-function theory in the diffusion domain, *Phys. Chem. Earth (B)*, **24**, 177-185 (Erratum 757-765).

Time-dependent diffusion theory for reflected fluxes:

Summary of scaling relations for uniform slabs

H: cloud *physical* thickness "extinction" [collision probability / m]

τ: cloud *optical* thickness ($\sigma H = H$ / Mean-Free-Path)

g: asymmetry factor of the scattering phase function

(i.e., $\langle\cos\theta_s\rangle = 2\pi \int \cos\theta_s P(\theta_s) \sin\theta_s d\theta_s \approx 0.85$)

From "asymptotic" theory:

(i.e., scaling arguments based on random walk statistics)

prob of reflection: $R = 1 - T$, where $T \propto 1/(1-g)\tau$

mean path length: $\langle L \rangle_R = \langle ct \rangle_R \propto H$

RMS path length: $\langle L^2 \rangle_R^{1/2} = \langle (ct)^2 \rangle_R^{1/2} \propto H \times \sqrt{(1-g)\tau}$

RMS spot size: $\langle \rho^2 \rangle_R^{1/2} \propto H / \sqrt{(1-g)\tau}$

Application to SNR Estimation

$$R = 1 - T = \frac{(1-g)\tau}{2\chi + (1-g)\tau}$$ (Schuster, 1905)

$$\left.\begin{aligned} &\langle t \rangle_R \approx H / c \\ &\langle \rho^2 \rangle_R \approx H\ell_\mathrm{t} = H^2 / (1-g)\tau \end{aligned}\right\}$$ "back-of-envelop" estimates

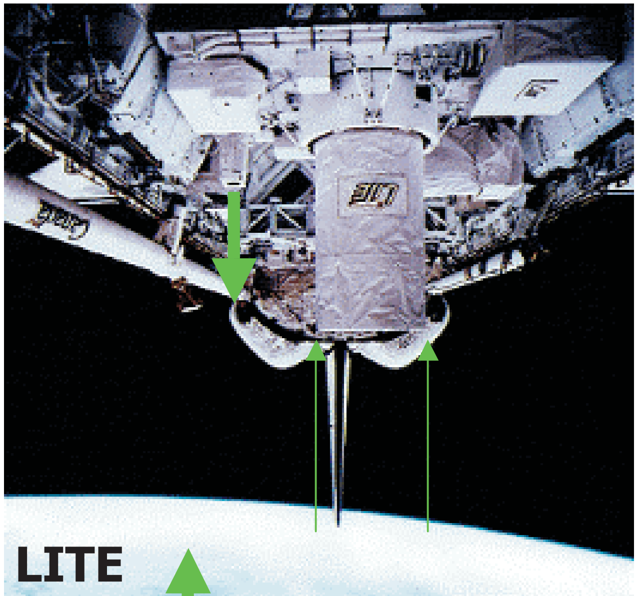
$$S(\delta t, \Delta T) \approx [\frac{1}{\pi}(\overbrace{E_\mathrm{p} / h\nu}^{\text{photons/pulse}}) \times \overbrace{R / \langle t \rangle_R / \pi \langle \rho^2 \rangle_R}^{\approx R\times(1-g)\tau\times c/H^3}] \times (\overbrace{A\delta\Omega}^{\text{étendue}} \times \delta t) \times (\overbrace{f \times \Delta T}^{\text{number of pulses}})$$

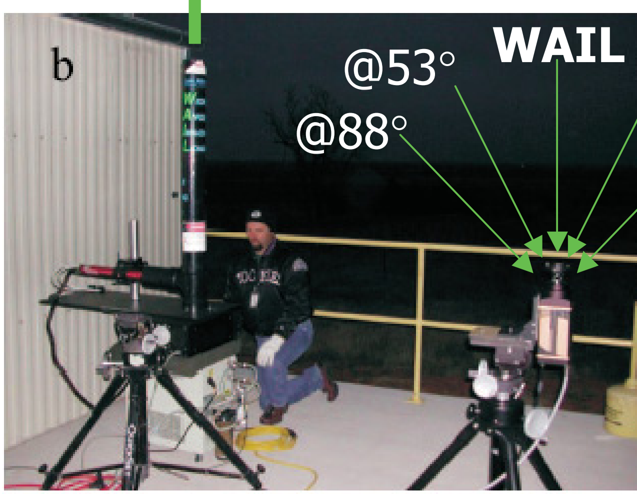
$$N(\delta t, \Delta T) \approx \sqrt{\underbrace{S(\delta t, \Delta T)}_{\text{shot noise}} + \underbrace{(1-R) \times (F_{0\lambda} / \pi h\nu) \times \Delta\lambda \times A\delta\Omega \times \delta t}_{\text{solar or lunar background (use } R\text{, not } T=1-R\text{, if from above)}} + \text{Electronics}}$$

Transmitter ➔ E_p: pulse energy; f: repetition rate

Receiver ➔
- A: aperture (pupil) area; $\delta\Omega$: FOV (solid angle)
- $\Delta\lambda$: bandpass of background rejection filter
- δt: temporal bin size; ΔT: integration time

SNR: Space- vs Ground-Based



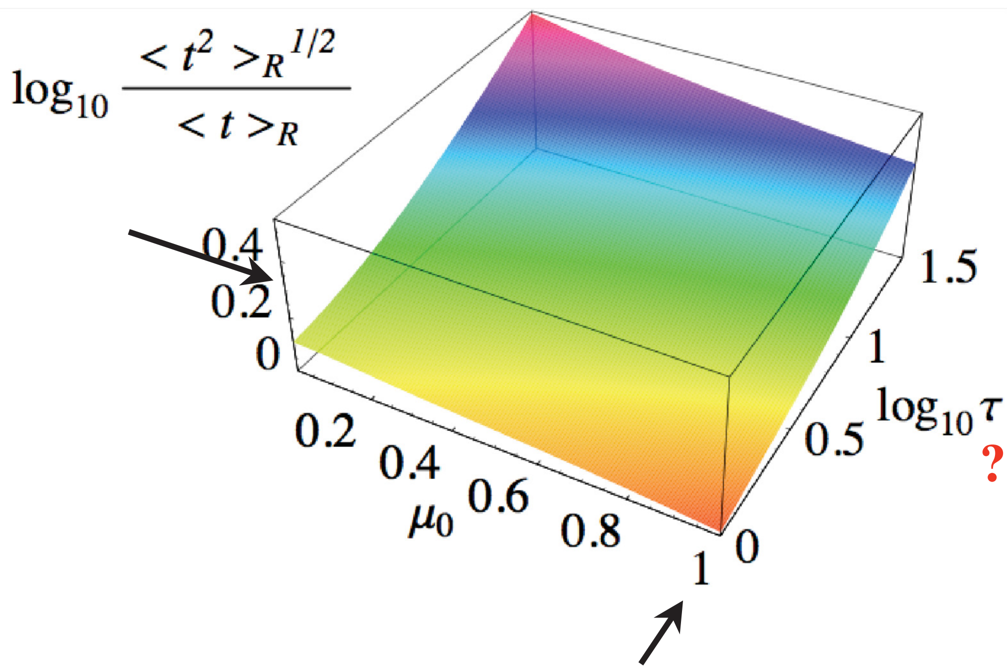


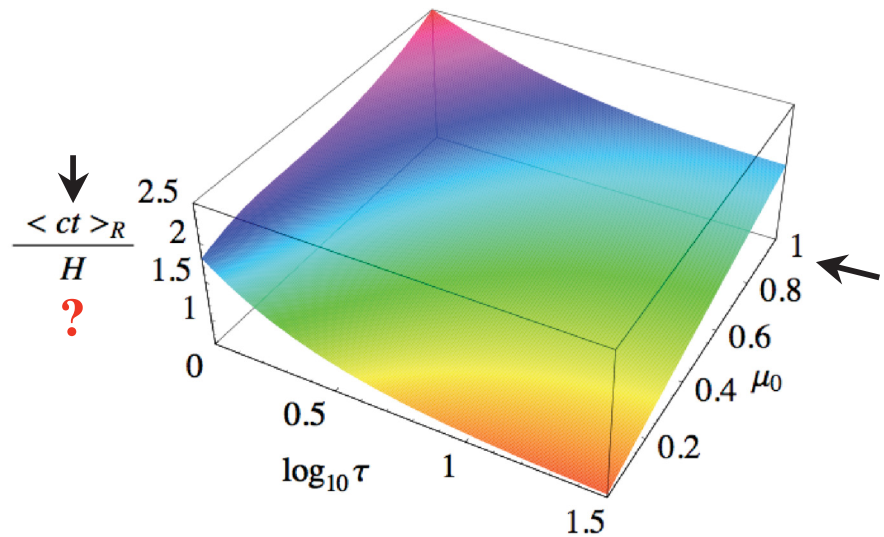
Davis, A. B., 2008: Multiple-scattering lidar from both sides of the clouds: Addressing internal structure, *J. Geophys. Res.*, **113**, D14S10-14S25, doi:10.1029/2007JD009666.

Quantity	Symbol	Unit	LITE	WAIL
Standoff distance	d_{obs}	km	259	0.7
Equation (56)	$\delta\Omega_{Gf}$	sr	$4\ 10^{-6}$	1.8
"Adapted" FOV[a]	$2\theta_{Gf}$	deg	0.06	91
	Transmitter Parameters			
Wavelength	λ	nm	532	532
Power = E_p × RepRate	P	W	5	5
Pulse frequency	RepRate	Hz	10	$12\ 10^3$
Pulse energy	E_p	mJ	500	0.42
Photons per pulse	$E_p\lambda/hc$	[−]	$1.34\ 10^{18}$	$1.12\ 10^{15}$
	Receiver Parameters			
Optical throughput	OTp	%	45[b]	70
Quantum efficiency	η_λ	%	14	70
Aperture area (effective)	A	m^2	0.63	10^{-5}
FOV (full width)[a]	$2\theta_{max}$	deg	0.20	88
$\delta\Omega_{FOV}$/U1R_to_F	$\frac{2(1-\cos\theta_{max})}{(1-\cos 2\theta_{max})/2}$	[−]	$1 + 3\ 10^{-6}$	1.163
Étendue	A × U1R_to_F	$m^2 \cdot sr$	$6\ 10^{-6}$	$15.5\ 10^{-6}$
Filter bandpass	$\Delta\lambda$	nm	0.35	50
	Sampling and Averaging			
Path bin size	δct	m	10	10
Integration time	Δt	s	0.1	300
Number of pulses	N_p	[−]	1	$3.6\ 10^{6}$[c]
	Predictions			
Signal	$S_{\delta ct}(\Delta t)$	counts	2721[b]	$341\ 10^3$
Only shot noise	SNR_{night}	[−]	78	584
+ lunar background	SNR_{+moon}	[−]	38	19
+ solar background	$SNR_{daytime}$	[−]	$4.3\ 10^{-2}$	$2.6\ 10^{-2}$

$H = 0.5$ km, $\tau = 25$

Time-dependent diffusion theory for reflected fluxes:
Exact diffusion theory, with collimated beam





Davis, A. B., I. N. Polonsky, and A. Marshak, 2009: Space-Time Green Functions for Diffusive Radiation Transport, in Application to Active and Passive Cloud Probing, *Light Scattering Reviews, Vol. 4*, A. A. Kohkanovsky (Ed.), Chapter 5, pages 169-292, Springer, Heidelberg (Germany).

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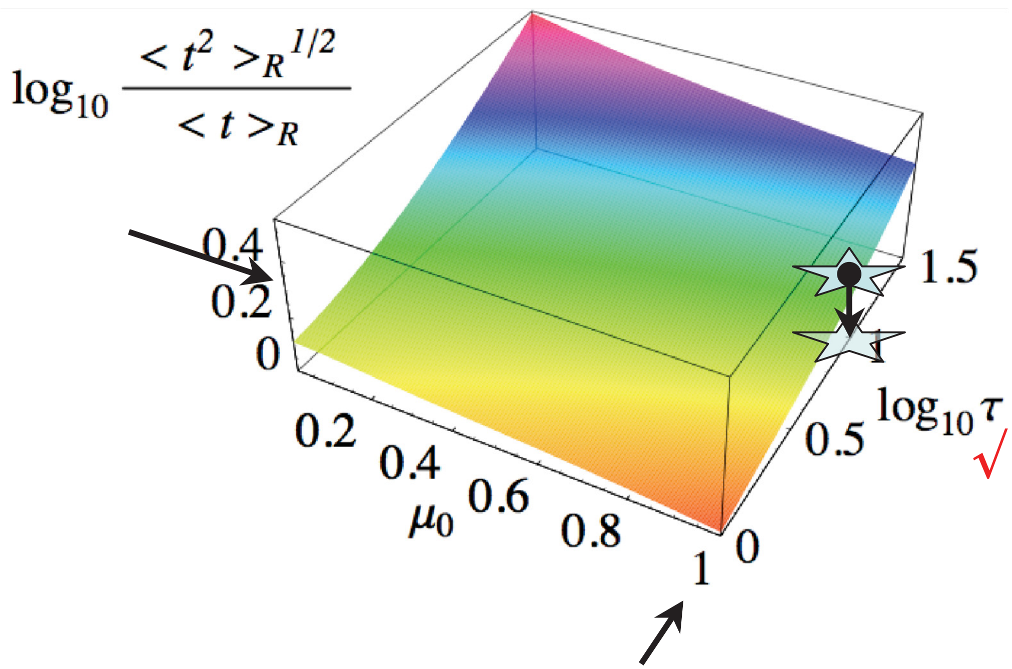

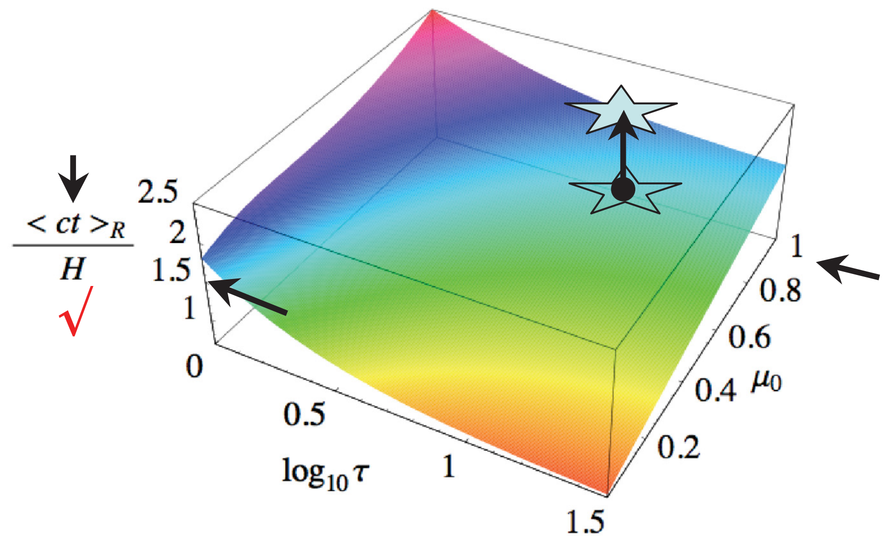

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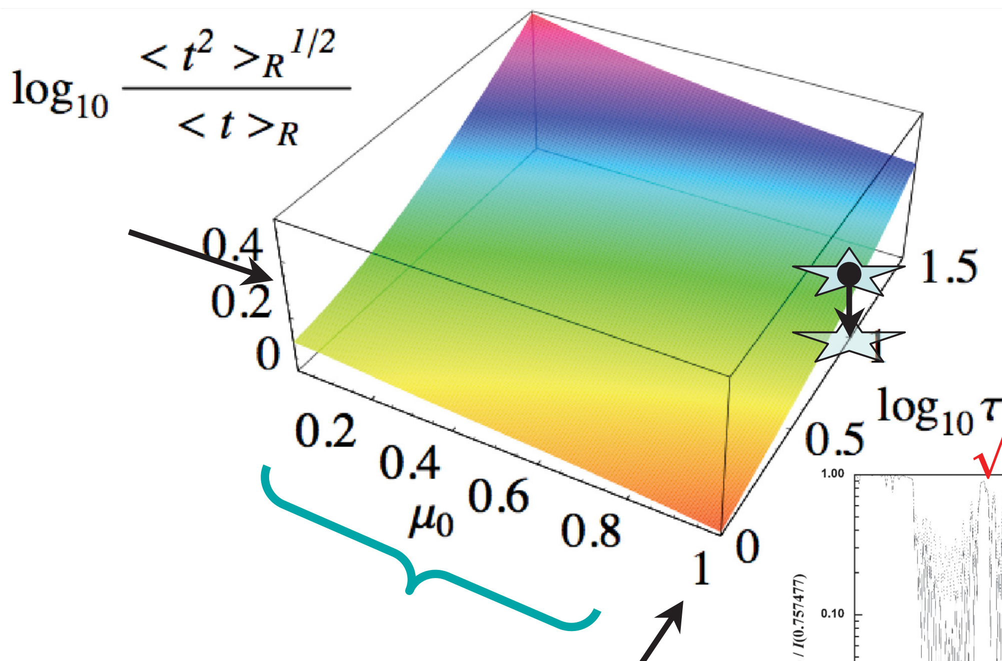
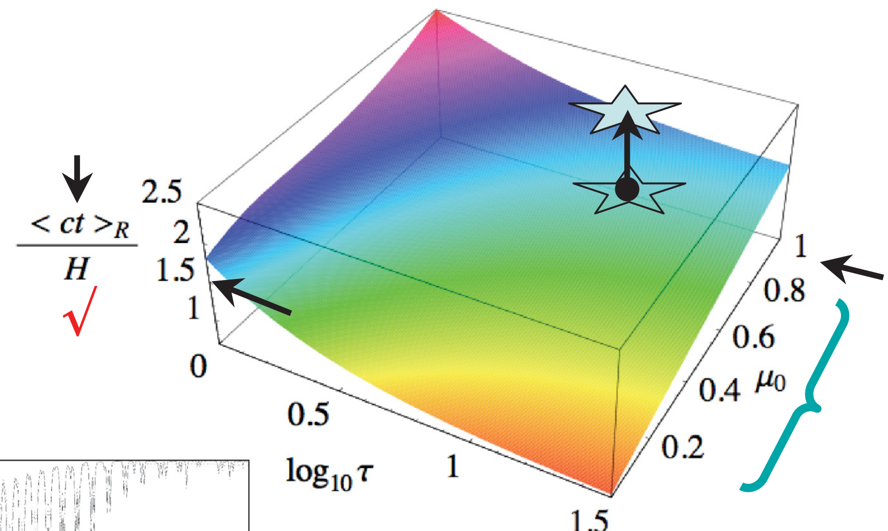
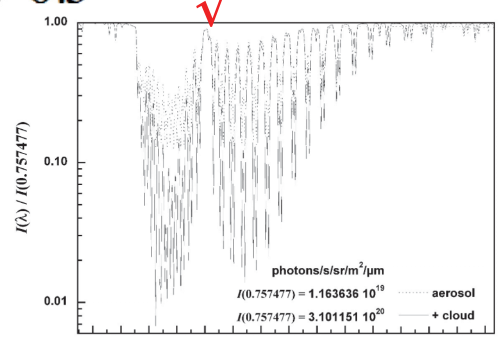
Time-dependent diffusion theory for reflected fluxes:
Exact diffusion theory, with collimated beam

Space-based hi-res O_2 A-band (passive modality, same physics)

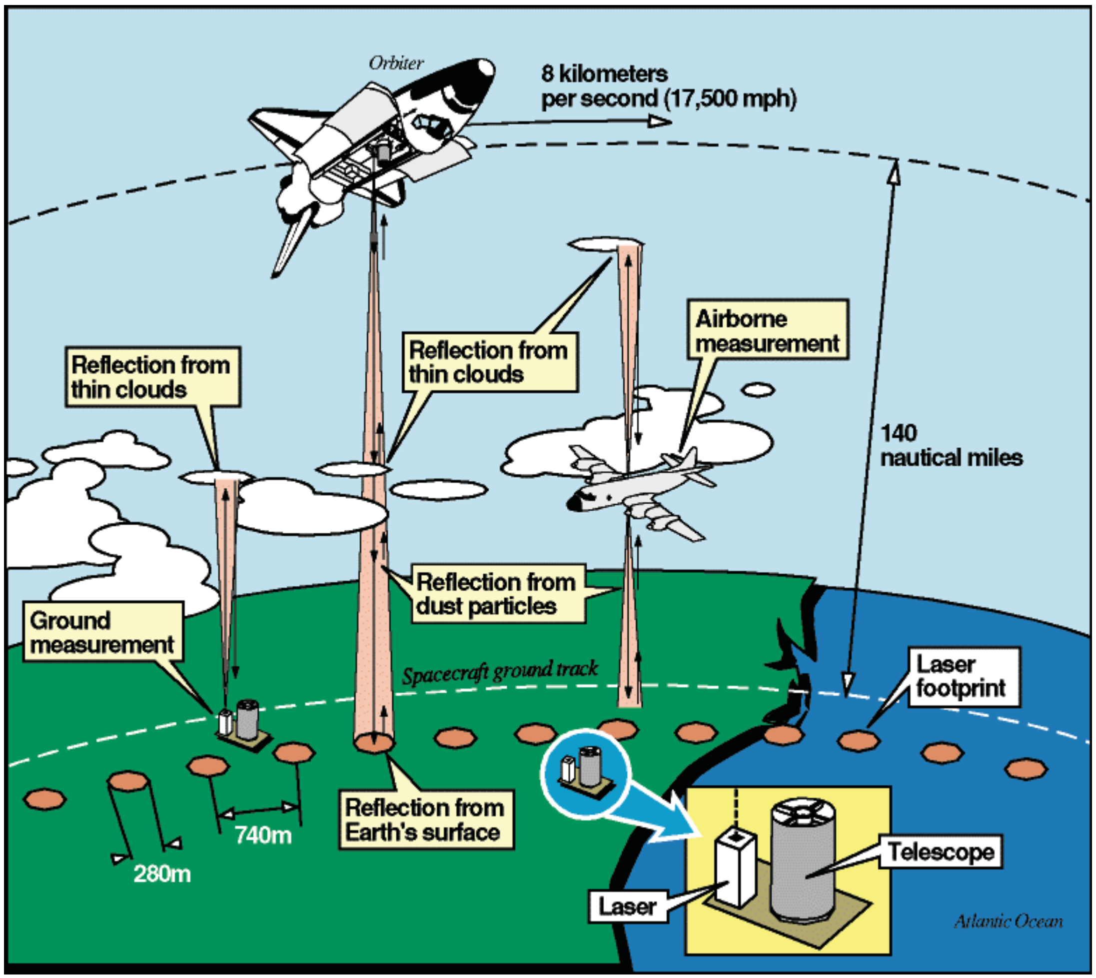


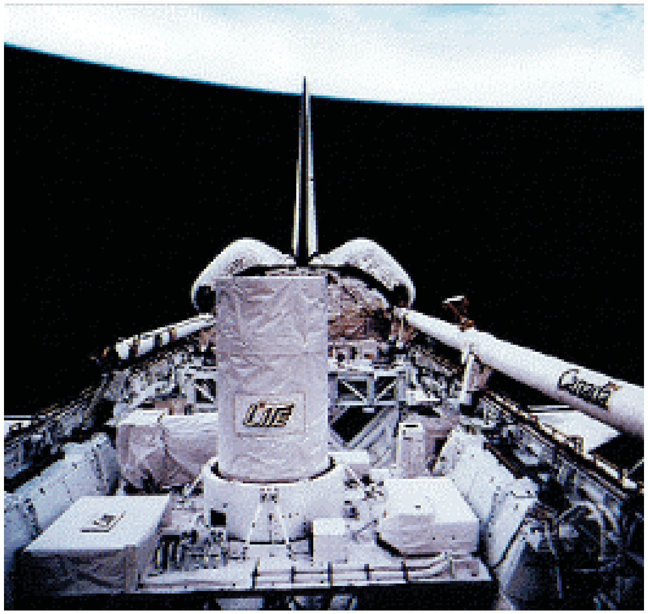




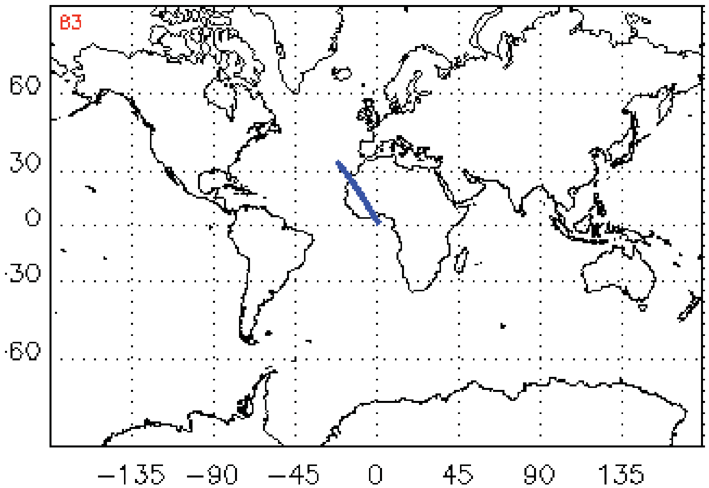
Davis, A. B., I. N. Polonsky, and A. Marshak, 2009: Space-Time Green Functions for Diffusive Radiation Transport, in Application to Active and Passive Cloud Probing, *Light Scattering Reviews, Vol. 4*, A. A. Kohkanovsky (Ed.), Chapter 5, pages 169-292, Springer, Heidelberg (Germany).

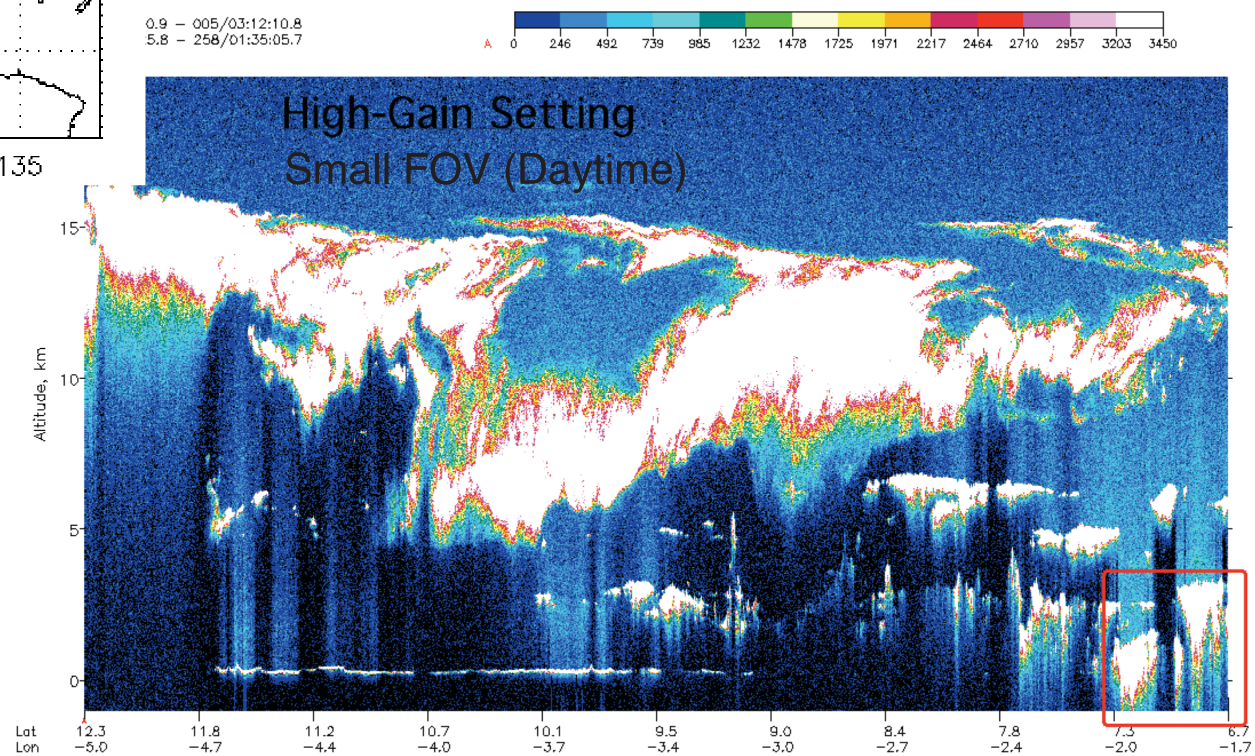
Lidar-In-space Technology Experiment (LITE) Space Shuttle Discovery STS-64 mission, September 9-20, 1994



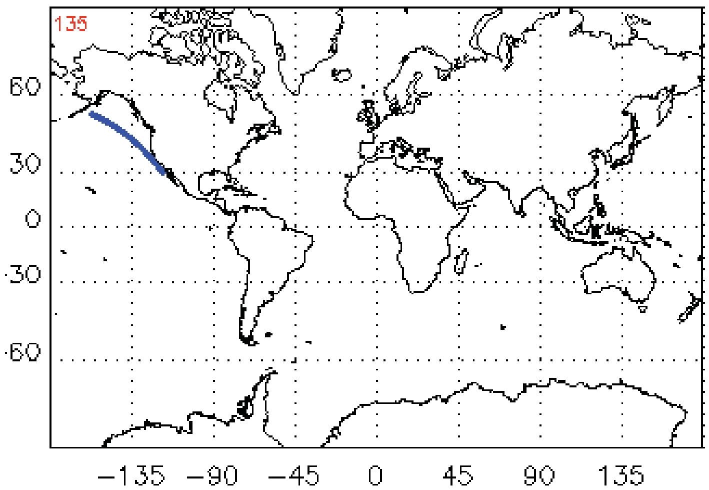


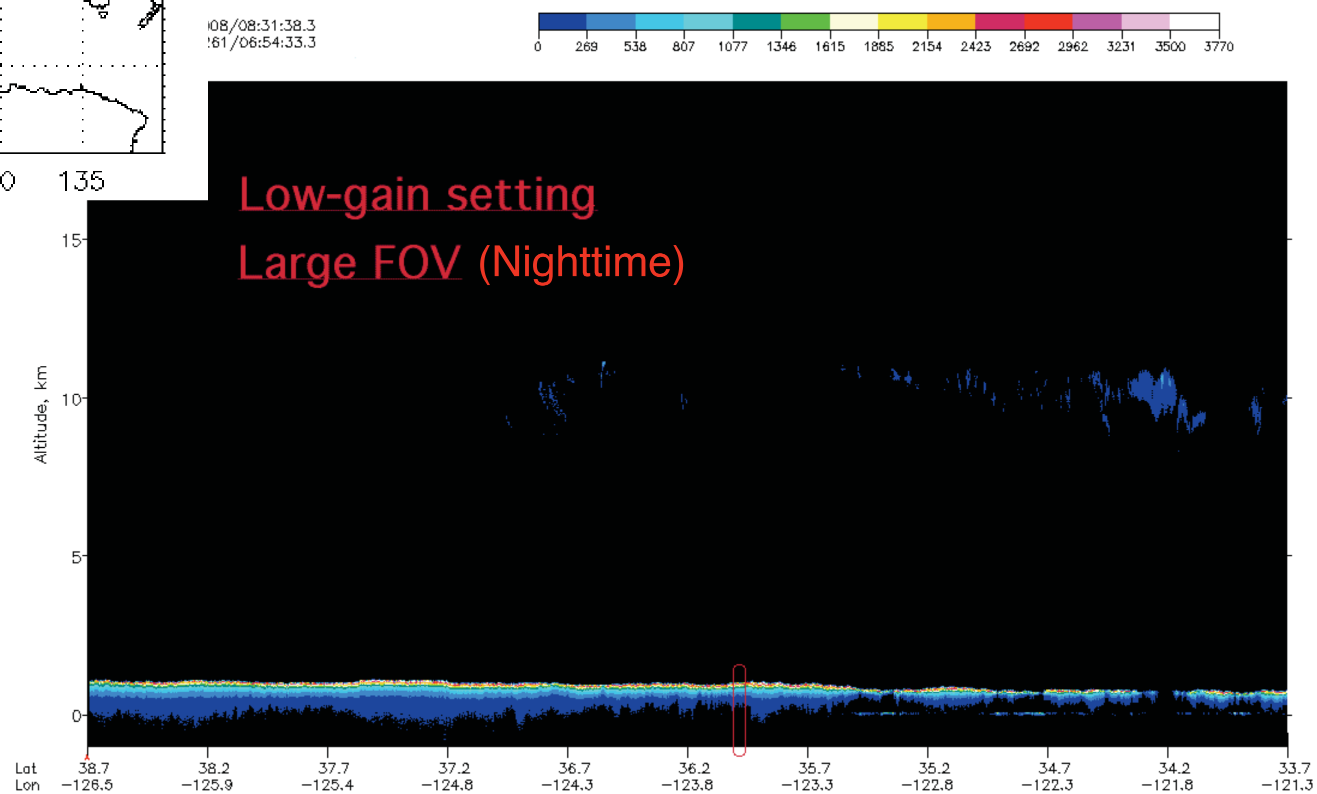
Typical LITE transect: Interesting



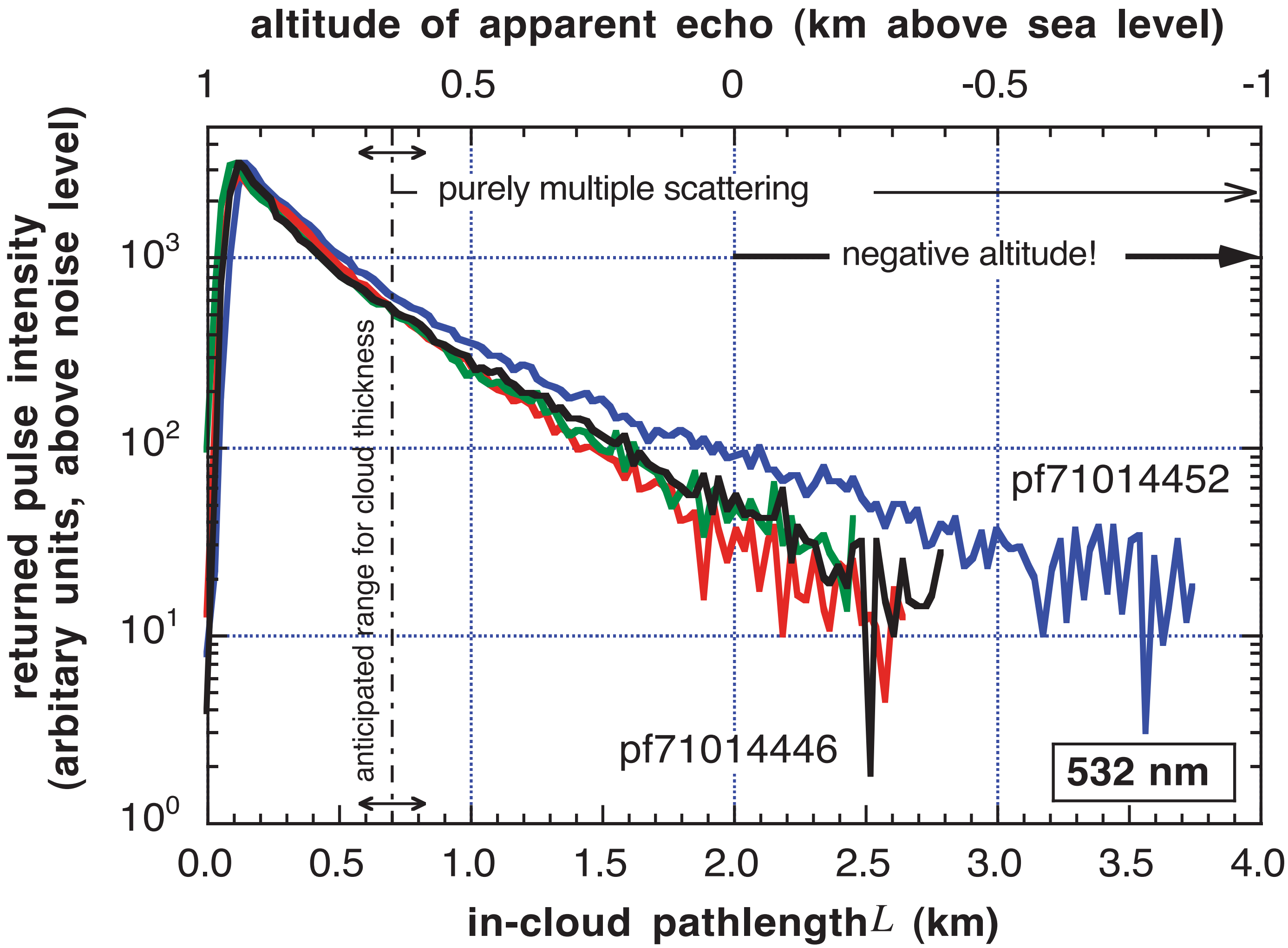


LITE transect of interest here!



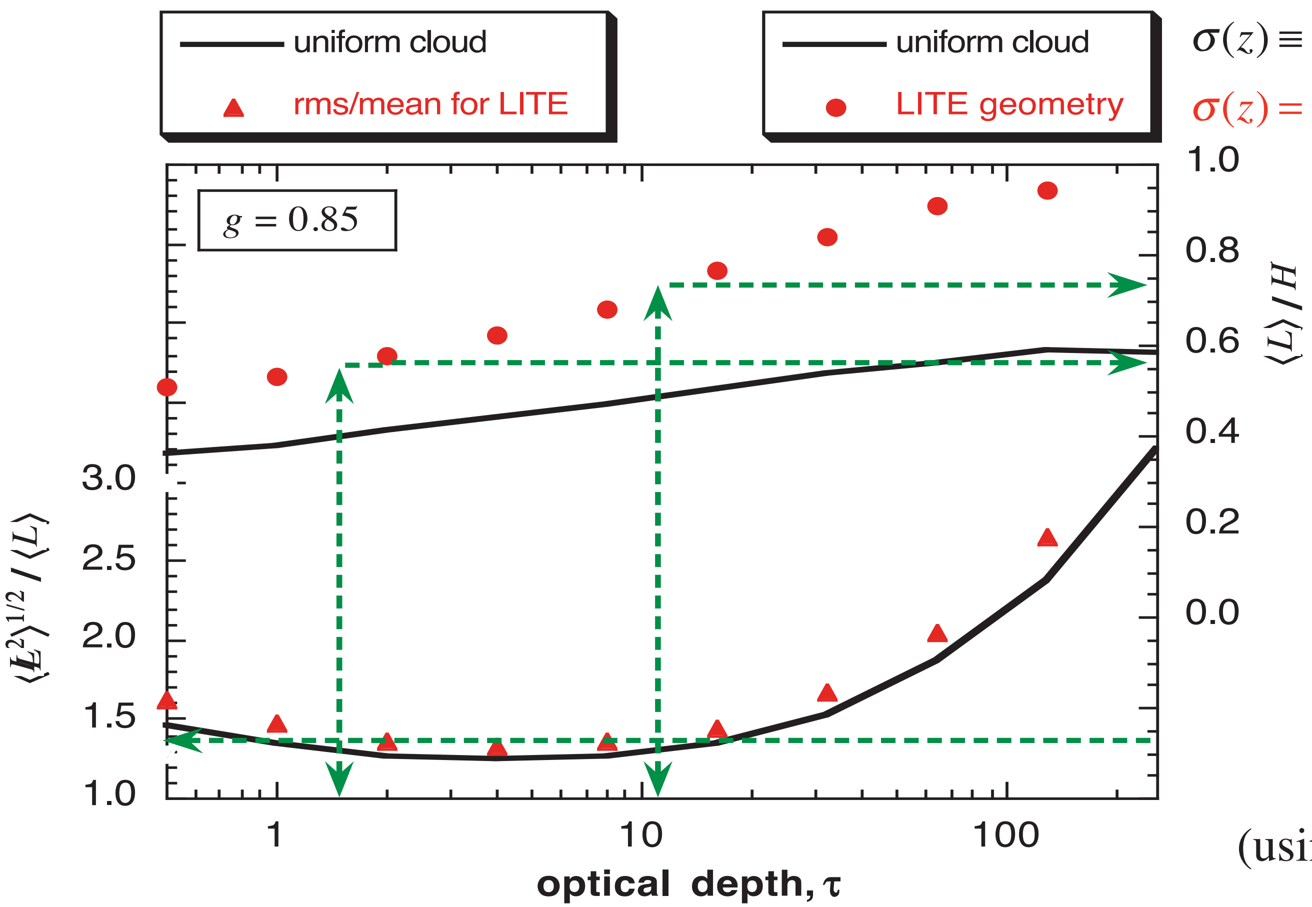


The four non-saturated LITE returns from nighttime orbit #135



Not about “ranging” per se, rather an **impulse response** of an optical medium.

2-parameter retrieval for clouds: From first 2 temporal moments



$\sigma(z) \equiv \tau / H$, or ...

$\sigma(z) = (\zeta+1)\tau / H \times (z/H)^{\gamma}, 0 < \gamma \leq 1$

$\langle L \rangle \approx 0.515$ km

$\langle L^2 \rangle^{1/2} / \langle L \rangle \approx 1.38$

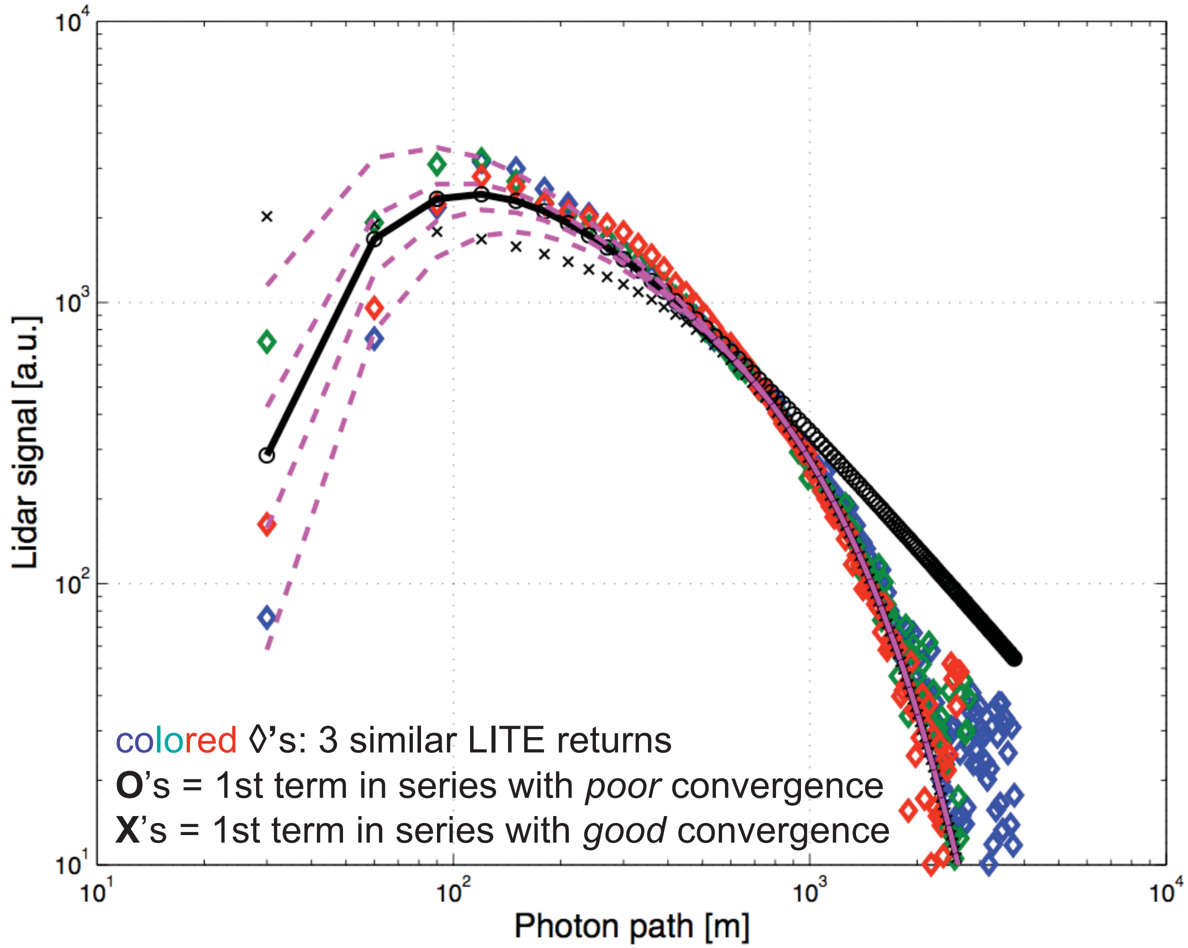
$\tau \approx 11$

$H \approx 0.38$ km

(using $\gamma = 1$ stratification model)

Davis, A. B., D. M. Winker, and M. A. Vaughan, 2001: First Retrievals of Dense Cloud Properties from Off-Beam/Multiple-Scattering Lidar Data Collected in Space, in *Laser Remote Sensing of the Atmosphere: Selected Papers from the 20th International Conference on Laser Radar*, Vichy (France), July 9-14, 2000, Eds. A. Dabas and J. Pelon, École Polytechnique, Palaiseau (France), pp. 35-38.

2-parameter retrieval for clouds: From new lidar equation in time



Note log-log axes

Nonlinear least-squares fit over relevant range

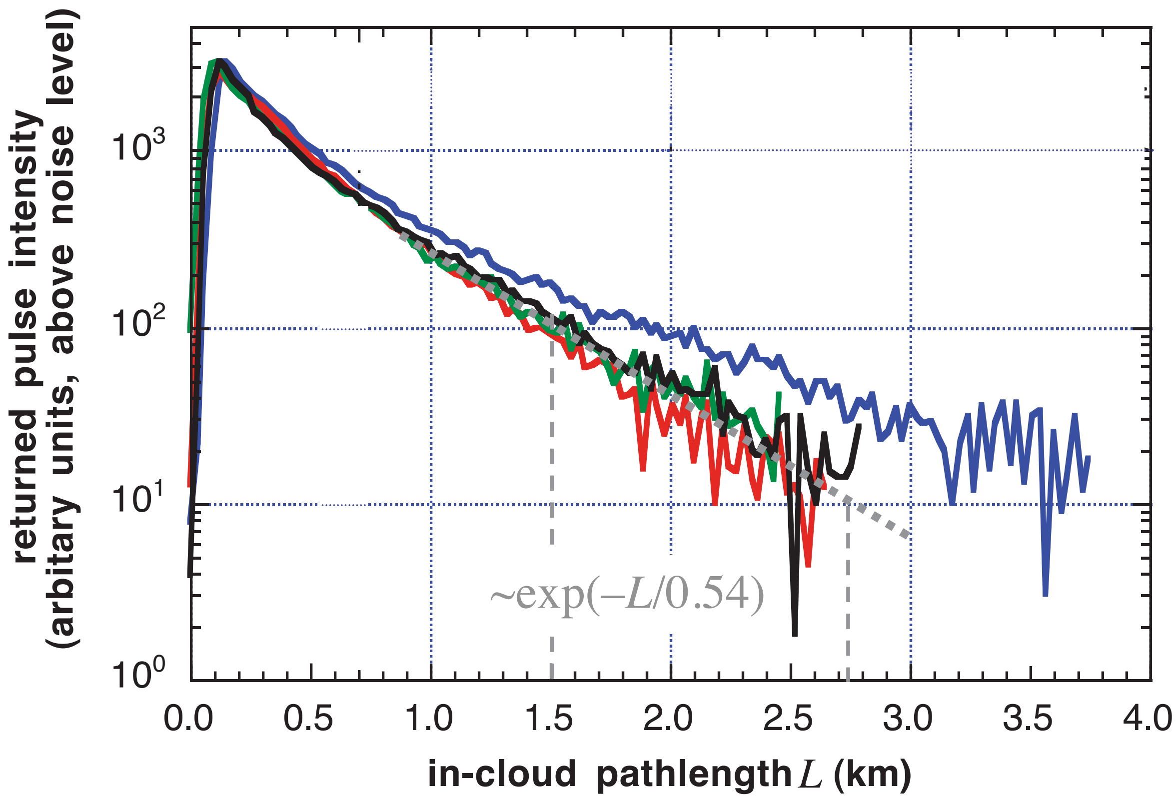
$\tau \approx 20$

$H \approx 0.25$ km

(consistent with uniform $\gamma = 0$ model for two first moments on the previous slide)

Polonsky, I. N., and A. B. Davis, 2005: *Off-Beam Cloud Lidar: A New Diffusion Model and an Analysis of LITE Returns*, LANL Report, LA-14219, Los Alamos National Laboratory, Los Alamos (NM).

2-parameter retrieval for clouds: From time-integral & decay rate



(1) Estimate cloud albedo $R \approx \pi I / E_{\mathrm{p}}$ from I, time-integral of calibrated radiance and compute τ from

$$R(\tau) = \frac{\tau}{\tau + 2\chi / (1-g)}$$

(2) Estimate decay rate L^* for exponential tail and obtain H from

$$L^* = H \times \frac{3(1-g)\tau}{\pi^2 R(\tau)^2}$$

Consistency check with uncalibrated data:

Using retrieval results from previous slide, (1) yields $R = 0.69$.

Using the same two cloud parameter values, the empirical estimate of $L^* = 0.54$ km in (2) yields $R = 0.65$ (6% difference).

Platforms for Multiple-Scattering Cloud Lidar

In summary, a wide range of stand-off distances:

- **Ground-based systems**
  - *Wide-Angle Imaging Lidar (WAIL)* at LANL
  - New receiver using MPL transmitters?
  - CW & time-only concepts?

… now eye-safe, and wider FOV

- **Airborne systems**
  - Above clouds: *THickness from Off-beam Returns (THOR)*, developed at NASA - Goddard Space Flight Center
  - Inside clouds: *"In-situ" cloud lidar* at U. of Co & SPEC
  - Maybe UAVs? Using CW?
- **Space-based systems**
  - *Lidar-in-space Technology Experiment (LITE)*, Space Shuttle, September 1994
  - Large FOV "channel" on a future lidar mission?
  - Complete during daytime with O_2 A-band spectroscopy?

Thank you!

Questions?

Funding from: